DEVELOPING A TEST TO EVALUATE SETTLEMENT CRACKING PERFORMANCE

By
Ryan Brettmann
David Darwin
Matthew O'Reilly

A Report on Research Sponsored by

THE ACI FOUNDATION

Structural Engineering and Engineering Materials
SL Report 15-2
May 2015

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

DEVELOPING A TEST PROCEDURE TO EVALUATE SETTLEMENT CRACKING PERFORMANCE

By

Ryan Brettmann

David Darwin

Matthew O'Reilly

A Report on Research Sponsored by

THE ACI FOUNDATION

Structural Engineering and Engineering Materials
SL Report 15-2

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
LAWRENCE, KANSAS
May 2015

ABSTRACT

A test procedure was developed to evaluate settlement cracking in concrete. The procedure was used to evaluate the effects of slump and the addition of either Acti-Gel® 208 or FORTA-FERRO® fibers on settlement cracking. The specimens consisted of 12×12×8 in. concrete blocks with No. 6 bars at 1.5 in. of cover to the center of the bar (nominal clear cover of $1^1/_8$ in.). Various methods of finishing and curing the specimens were investigated. It was found that covering the specimens with sloped hard plastic enclosed in plastic sheeting was a suitable method for obtaining unblemished specimens with clearly visible settlement cracks. The procedure was used to test 38 concrete mixtures with slumps ranging from ½ to 9 in. Of the 38 mixtures, 24 were control mixtures, 8 contained 2¼-in. FORTA-FERRO® fibers, and 6 contained Acti-Gel® 208, a rheology modifier and anti-settling agent. Average crack length, normalized to the length of the bar, was calculated for each mixture. Although there is significant scatter to the data, increasing slump increases the amount of settlement cracking. Initial results suggest that the addition of Acti-Gel® 208 to concrete decreases the amount of settlement cracking. Initial results also suggest that the addition of FORTA-FERRO® fibers to concrete decreases the amount of settlement cracking. There is a significant amount of scatter in the data for mixtures with similar slumps.

Key Words: settlement cracking, FORTA-FERRO® synthetic fibers, Acti-Gel® 208, bridge decks, high-performance concrete, slump, plastic shrinkage cracking

ACKNOWLEDGEMENTS

This report is based on research performed by Ryan Brettmann in partial fulfillment of the requirements for the MSCE degree from the University of Kansas. Support was provided by the ACI Foundation and sponsoring organizations: ABC Polymers, the ACI Foundation's Strategic Development Council (SDC), Active Minerals International, the American Society of Concrete Contractors, Baker Concrete Construction, BASF Corporation, FORTA Corporation, the Expanded Shale, Clay and Slate Institute, the Euclid Chemical Company, the University of Kansas Transportation Research Institute, PNA Construction Technologies, Inc., Premier Construction Products, Sika Corporation, Structural Group, Inc., and W. R. Grace and Company.

INTRODUCTION

Deterioration of concrete bridge decks increases maintenance costs and decreases the service life of these structures. Cracking significantly contributes to this deterioration by providing a pathway for water and deicing chemicals to penetrate the concrete and corrode the steel reinforcement. Corrosion of the reinforcement can limit the service life of the structure and may require the repair or replacement of the deck. A report by the Transportation Research Board (1979) stated that approximately one-third of the highway bridge decks in the United States were severely damaged by corrosion and that it would take $6.3 billion to repair these bridges. In 2013, the American Society of Civil Engineers reported that it would cost $76 billion to repair or replace the nation’s deficient bridges. Factors that affect cracking include concrete mixture proportions, construction practices, weather conditions, and bridge deck age.

The University of Kansas has been working with the Kansas Department of Transportation (KDOT), and 18 other departments of transportation, through a pool-funded study with the goal of minimizing bridge deck cracking. The study consists of two main components: laboratory tests and field application. In the laboratory, concrete mixtures are tested for compressive strength, free shrinkage, freeze-thaw durability, scaling resistance, air-void system stability, and most recently settlement cracking. The results of this research have been used to develop low-cracking high-performance concrete (LC-HPC) specifications to improve the cracking performance and overall durability of concrete bridge decks. In the field, LP-HPC specifications have been used to design and construct 17 bridges in Kansas. In addition, 11 control bridges were built in accordance to the standard Kansas Department of Transportation specifications as a basis for comparison. Annual crack surveys have indicated that all but one of the LC-HPC bridges are exhibiting less cracking than their corresponding control decks

(Lindquist et al. 2008, Gruman et al. 2009, McLeod et al. 2009, Darwin et al. 2010, 2012, Yuan et al. 2011, Harley et al. 2011, Bohaty et al. 2013, Pendergrass and Darwin 2014). LC-HPC specifications have been revised based on findings in the laboratory tests or field studies. The most recent version of the specifications is presented by Pendergrass and Darwin (2014).

This report focuses on the development of a test for settlement cracking in the laboratory. Settlement, or subsidence, cracking occurs when fresh concrete continues to settle around rigid inclusions, such as reinforcing steel, after consolidation is completed. As the concrete settles around the reinforcement, local tensile stresses develop above the steel. This effect causes a weakened region of concrete directly above the bars resulting in settlement cracks directly above and parallel to the steel reinforcement. Currently, there is a lack of a standardized test for settlement cracking in concrete. The next section will describe the previous work that has been completed regarding settlement cracking.

PREVIOUS WORK

Dakhil, Cady, and Carrier (1975): Dakhil et al. (1975) studied the effect of depth of cover, concrete slump, and reinforcing bar size on settlement cracking using 108 specimens. Slumps of 2, 3, and 4 in., cover depths of 0.75, 1.5, and 2 in., and bar sizes of No. 4, No. 5, and No. 6 were used. Three specimens were cast for each combination of variables. The specimens were fabricated in 12×12×8 in. forms with holes drilled on opposite sides to suspend a reinforcing bar. The concrete was then vibrated with an electric vibrator, screeded in the direction parallel to the reinforcement, and finished with a wet burlap drag. Four hours later, the specimens were photographed and visually inspected for cracks. A specimen was considered to be cracked if a crack that was visible to the unaided eye existed above the bar. Dakhil et al.

(1975) observed that higher slumps, lower concrete cover, and larger bar sizes increased the incidence and severity of cracking. Furthermore, the researchers concluded that concrete cover depth was the most important variable affecting cracking.

Dakhil et al. (1975) also examined whether settlement cracking increased the corrosion of steel reinforcement. Specimens with No. 5 reinforcing bars and 0.75 and 1.5 in. covers from the cracking portion of this study were used. The specimens were moist cured for a week and then air dried. Next, a caulking compound was added to the perimeter of the specimens as a barrier for holding a salt solution. Initial potential readings of the steel were taken for each specimen with respect to a copper-copper sulfate electrode. A 5% sodium chloride solution was then added to the surface of the specimens. Initially, the solution was added every eight hours until the solution penetrated the concrete. Subsequently, the solution was added every 24 hours. Potential readings were taken between additions of the solution. The readings were initially taken daily, but later they were taken three times per week. The results indicated that all of the cracked specimens had potentials corresponding to the active corrosion range, while the uncracked specimens were in the inconclusive area between the passive and active corrosion regions. Dakhil et al. (1975) concluded that settlement cracking plays a significant role in the corrosion of steel reinforcement.

Weyers, Conway, and Cady (1982): Weyers et al. (1982) studied the influence of adjacent inclusions and spacing between inclusions on settlement cracking. The study involved casting gelatin mixtures into 22×1×8.5 in. wood forms with plexiglass sheets bolted to the form. Three threaded brass rods with diameters of 0.625 in. were included at 3, 4.5, and 6 in. spacing. The cover depth was 1 in. Additional cover depths of 1.5, 2, and 2.5 in. were also investigated for the 6-in. spacing. The gelatin mixture was composed of 16% glycerine, 8% gelatin, and 76%

tap water, by weight. A model mold is shown in Figure 1. After the gelatin set, a photoelastic analysis was performed to examine the stress distributions around the reinforcement. Weyers et al. (1982) concluded that cover depth, inclusion spacing factors, and consistency of the mixture all influence the stress distribution and magnitude in the region surrounding the inclusions. Increasing cover depth decreased the tangential surface stress above the central inclusion while increasing the spacing factor of the inclusions did not have a consistent effect on stress.

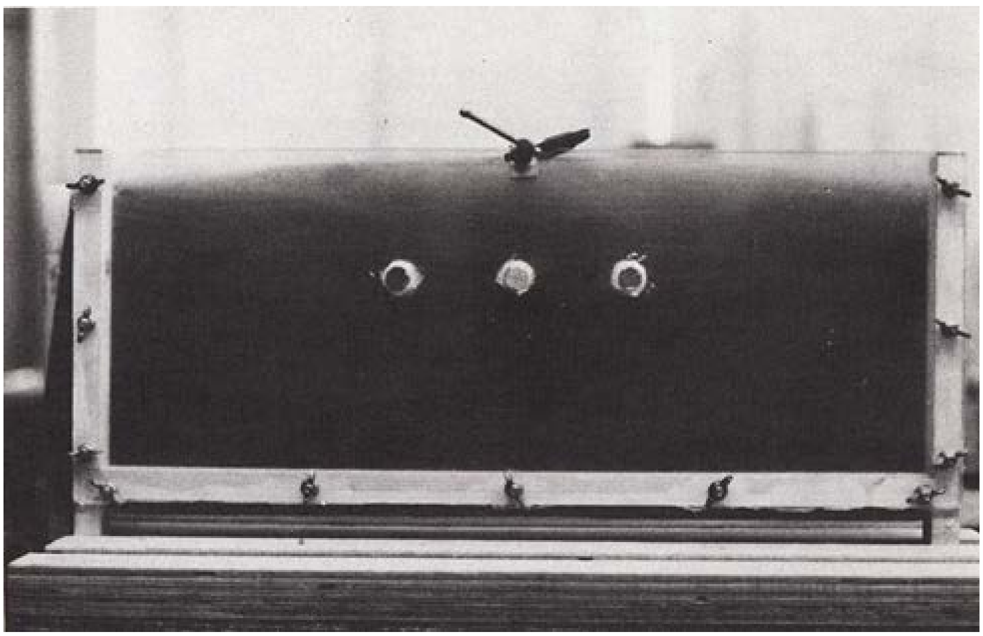

Figure 1: Gelatin Mold from Weyers et al. (1982)

Babaei and Fouladgar (1997): Babaei and Fouladgar (1997) studied factors that influence concrete cracking in bridge decks. Practical design and construction methods used to mitigate cracking were also presented. The researchers noted that plastic shrinkage, settlement, thermal shrinkage, drying shrinkage, and flexure contribute to bridge deck cracking.

Babaei and Fouladgar (1997) agree with Dakhil et al. (1975) that settlement cracking increases with decreasing concrete cover, increasing slump, and increasing reinforcing bar size.

They also stated that the weakened planes of concrete above the reinforcing bars as a result of settlement increased the probability of cracking in that region due to other factors, such as drying shrinkage, thermal shrinkage, or flexure. To minimize this effect in bridge decks they recommended that, for slabs with uppermost reinforcement perpendicular to traffic, top and bottom transverse bars should be offset and that the size of top transverse reinforcement should be limited to No. 5 bars.

Suprenant and Malisch (1999): Suprenant and Malisch (1999) performed a follow-up to the study by Dakhil et al. (1975) to determine the effect of synthetic fibers on settlement cracking for different cover depths, concrete slumps, and reinforcing bar sizes. Suprenant and Malisch (1999) believed that the addition of synthetic fibers would reduce settlement cracking by reducing bleeding (so that the concrete would exhibit less settlement) and by increasing the tensile strength of the mixture. In the study, 72 concrete specimens were analyzed with combinations of two slumps, three concrete covers, and two reinforcing bar sizes. Slumps of 4.5 and 5.5 in., cover depths of 0.5, 0.75, and 1 in., and bar sizes of No. 6 and No. 8 bar sizes were used. Fibermesh MD fibrillated propylene fibers were added to half of the specimens at a dosage rate of 1.25 lb/yd^3. Three specimens were cast for each combination of the variables. The forms and procedure were similar to that of the study completed by Dakhil et al. (1975). The concrete, however, was delivered by a single ready-mix truck. Forty minutes passed while the control specimens were cast before the fibers were added to the concrete in the truck, which had begun to stiffen. The specimens were also finished with a float instead of a burlap drag so that cracks were more visible. The specimens were inspected for settlement cracking after 4 and 18 hours. All of the fiber-free specimens exhibited settlement cracking while none of the specimens with fibers experienced cracking. Suprenant and Malisch (1999) concluded that synthetic fibers prevent settlement cracking, even under severe conditions. Because the concrete containing the fibers had a shorter time to set, and thus a shorter time to undergo settlement, than the concrete without fibers, it is not clear, however that the fibers alone limited settlement cracking.

Combrinck and Boshoff (2013): Combrink and Boshoff (2013) studied the origin of plastic settlement cracking and the effect of revibration on cracking. In the study, two specimens were cast in L-shaped molds with deep and shallow sections to serve as rigid inclusions to induce settlement cracking. The side panels of the molds were transparent so that cracks could be seen below the surface of the concrete. The experiment was conducted in an environmentally controlled laboratory, and the surfaces of the specimens were kept wet to deter evaporation. Both specimens cracked at the boundary between the deep and shallow sections of the molds. One of the specimens also had a crack below the surface of the concrete that could only be seen from the side panel. Images of the crack 80 and 360 minutes after casting show that the dominant crack forms within the concrete at the boundary between the sections. Therefore, the researchers concluded that settlement cracks form from the bottom upwards. This also implies that settlement cracks may be present in concrete even if they have not propagated to the surface. These observations were verified by a numerical analysis.

Combrink and Boshoff (2013) also analyzed the effect of revibration as a method to mitigate settlement cracking. Revibrating concrete before it loses plasticity can decrease the amount of settlement cracking, but also may have adverse effects on concrete strength. For this portion of the study, a number of concrete cubes were revibrated at the initial or final setting time, while the rest of the specimens were not disturbed. All of the specimens were then cured in water and tested after seven days. The results indicated that revibrating at the initial setting time increased the concrete strength while revibrating at the final setting time decreased the concrete strength. Combrink and Boshoff (2013) recommend that, if needed, revibration should be performed prior to the final setting time.

In a related study, Altowaiji, Darwin, and Donahey (1986) studied the effect of revibration on the bond strength between reinforcing steel and concrete. They observed that revibration improved the bond strength for top-cast (near upper surface) bars placed in high-slump concrete but "severely damaged" the bond strength of bars cast in well-consolidated, low-slump concrete.

OBJECTIVE AND SCOPE

Multiple studies at the University of Kansas have observed the significance of cracking on bridge decks (Schmitt and Darwin 1995, 1999, Miller and Darwin 2000, Lindquist et al. 2008, McLeod et al. 2009, Darwin et al. 2010, 2012, Yuan et al. 2011, Pendergrass et al. 2014). The cracks form primarily above and parallel to the reinforcement and increase in frequency as concrete slump is increased. This strongly implies that settlement is a principal cause of the cracking. Cracking is a substantial problem for bridges as the cracks provide a direct path for water and deicing chemicals to penetrate through the concrete deck and corrode the steel reinforcement.

The objective of this study is to develop a test procedure to evaluate the settlement cracking performance of concrete. It includes an examination of the effects of slump and the addition of FORTA-FERRO® fibers and Acti-Gel® 208 on settlement cracking.

EXPERIMENTAL PROGRAM

This section describes the experimental program that was implemented for designing, mixing, casting, and reading settlement cracking specimens.

Materials

Type I/II portland cement, Kansas River sand, pea gravel, and two gradations of granite with maximum sizes of 1 and ½ in. from Midwest Concrete Materials in Lawrence, KS were used. Aggregate properties are shown in Tables 1 through 4. A superplasticizer, MasterGlenium 3030, and an air entraining admixture, MasterAir AE 200, both from BASF Corporation, were used.

Acti-Gel® 208 from Active Minerals International and FORTA-FERRO® fibers from FORTA Corporation were also tested in this study. Acti-Gel® 208 is a rheology modifier and anti-settling agent made of fine magnesium aluminum-silicate mineral particles. FORTA-FERRO® fibers are comprised of 2¼-in. long synthetic twisted bundle monofilament fibers and are used to reduce concrete shrinkage, increase impact strength, and improve fatigue resistance. Acti-Gel® 208 and FORTA-FERRO® fibers are shown in Figures 2 and 3, respectively.

Table 1: Coarse Aggregate Properties (Granite A)

Specific Gravity	2.62
Fineness Modulus	7.24
Absorption	0.58%
Maximum Size Aggregate (in.)	1
Sieve Size	**Percent Retained on Each Sieve**
1 ½ in.	0.00%
1 in.	1.60%
¾ in.	23.25%
½ in.	72.74%
⅜ in.	2.11%
No. 4	0.00%
No. 8	0.00%
No. 16	0.00%
No. 30	0.00%
No. 50	0.00%
No. 100	0.00%
No. 200	0.00%
Pan	0.29%

Table 2: Coarse Aggregate Properties (Granite B)

Specific Gravity	2.62
Fineness Modulus	6.50
Absorption	0.58%
Maximum Size Aggregate (in.)	1/2
Sieve Size	**Percent Retained on Each Sieve**
1 ½ in.	0.00%
1 in.	0.00%
¾ in.	0.00%
½ in.	1.41%
⅜ in.	52.15%
No. 4	43.35%
No. 8	2.74%
No. 16	0.00%
No. 30	0.00%
No. 50	0.00%
No. 100	0.00%
No. 200	0.00%
Pan	0.35%

Table 3: Fine Aggregate Properties (Pea Gravel)

Specific Gravity	2.63
Fineness Modulus	4.82
Absorption	1.42%
Sieve Size	**Percent Retained on Each Sieve**
1 ½ in.	0.00%
1 in.	0.00%
¾ in.	0.00%
½ in.	0.00%
⅜ in.	0.00%
No. 4	13.76%
No. 8	63.44%
No. 16	17.92%
No. 30	2.53%
No. 50	1.04%
No. 100	0.57%
No. 200	0.30%
Pan	0.43%

Table 4: Fine Aggregate Properties (Sand)

Specific Gravity	2.62
Fineness Modulus	3.03
Absorption	0.47%
Sieve Size	**Percent Retained on Each Sieve**
1 ½ in.	0.00%
1 in.	0.00%
¾ in.	0.00%
½ in.	0.00%
⅜ in.	0.00%
No. 4	2.54%
No. 8	14.38%
No. 16	22.42%
No. 30	23.02%
No. 50	23.17%
No. 100	10.48%
No. 200	3.08%
Pan	0.92%

Figure 2: Acti-Gel® 208

Figure 3: FORTA-FERRO® Fibers

Mixture Proportions

The aggregate gradation used for the mixtures was determined using KU Mix, a mix design program developed at the University of Kansas. KU Mix optimizes aggregate gradation to produce LC-HPC mixtures that yield workable concrete at low cement paste contents. Lindquist et al. (2008) describes the use of KU Mix, and the program can be downloaded from https://iri.drupal.ku.edu/node/43.

Air entraining agent dosage rates were determined using trial batches. Superplasticizing agents were added as necessary to achieve desired values of slump. FORTA-FERRO® fibers and Acti-Gel® 208 were added at dosage rates of 3 lb/yd^3 (0.2% by volume) and 0.05% by dry weight, respectively.

On a cubic yard basis, the mix design included 500 lb of cement, 250 lb of water, 453 lb of granite A, 893 lb of granite B, 576 lb of Pea gravel, and 60 mL of sand as shown in Appendix A. The water to cement ratio for the mixtures was 0.50 and the cement paste (cement plus water) content was 24.26% by volume.

Mixing Procedure

The coarse aggregate was soaked in water for at least 24 hours and then prepared to a saturated surface-dry condition in accordance with ASTM C127. The fine aggregate was prepared in a wet condition, and the free surface moisture was determined in accordance with ASTM C70. The batch water was adjusted to account for the excess surface moisture of the fine aggregate.

A counter-current pan mixer was used to mix the concrete in accordance with ASTM C192. Prior to mixing, the pan and mixing blades were dampened. Initially, all of the coarse aggregate and 80% of the mixing water were added to the mixer. The cement then was added to the mixer as it was turned on. After 1.5 minutes, the fine aggregates were added. After two more minutes of mixing, the superplasticizer, if any, was combined with 10% of the mixing water and added to the mixture. A minute later, the air entraining agent was combined with 10% of the mixing water and added to the mixture. After three more minutes of mixing, the mixer was stopped for five minutes, with damp towels covering the mixture to prevent evaporation. The concrete temperature was measured. After the resting period, the concrete was mixed for three more minutes. Liquid nitrogen was used, if necessary, to maintain temperature control. At this point, mixing was stopped, and slump and temperature tests were performed in accordance with ASTM C143 and ASTM C1064, respectively. FORTA-FERRO® fibers or Acti-Gel® 208, if used, were added to the mixture prior to an additional five minutes of mixing time, after which the slump and temperature tests were performed again. The concrete was then placed in a wheelbarrow and moved to an environmentally controlled laboratory (relative humidity of 50% ± 4% and a temperature of 73° ± 3° F) where the specimens were cast.

Test Specimens and Casting

Forms for the settlement cracking specimens were 12×12×8 in. and consisted of 0.75 in. thick plywood sheets with holes drilled on opposite sides of the form at a distance of 1.5 in. from the top. A No. 6 reinforcing bar was threaded at the ends and supported by 1.75 in. 10-24 machine screws producing a nominal clear cover of $1^1/_8$ in. The edges of the form were sealed with caulk and the inside of the form was coated with baby oil. Three forms were prepared for each concrete mixture. The forms are shown in Figure 4.

Figure 4: Forms

The three forms were filled with in two separate lifts of approximately equal depths. After each lift, the concrete was consolidated using a $1^{1}/_{8}$ in. diameter DEWALT DC530 cordless pencil vibrator until coarse aggregate was no longer visible on the surface. After the second lift was consolidated, the concrete was screeded with $20\times2\times^{3}/_{4}$ in. plywood and finished with a $16\times3\times^{1}/_{4}$ in. hand float.

Development of curing procedure

This section describes the development of the procedure used to cure the specimens after they are finished. All of the specimens for the intermediate procedures described below were cast with control mixtures as a means for comparison. For each procedure, the specimens were stored in the environmentally controlled laboratory for 24 hours after casting.

Specimens uncovered

In the original procedure, the specimens were left uncovered for 24 hours in the environmentally controlled laboratory. However, the results from this method were inconsistent. Since the specimens were exposed to the environment, it is likely that small differences in surface evaporation rates and their effect on plastic shrinkage cracking, even small, altered the results. Plastic shrinkage cracking occurs in fresh concrete when the evaporation rate from the surface exceeds the rate at which bleed (internal) water reaches the surface. This results in tensile stresses in the still plastic concrete, which cause cracking due to the differential volume change that occurs between the concrete at the surface and the interior. For this study, the objective was to determine the effects of settlement cracking exclusively. Therefore, a new method was necessary to eliminate the influence of plastic shrinkage cracking.

Specimens covered with burlap

To reduce the effect of plastic shrinkage cracking, the procedure was altered to include covering the specimens with wet burlap, as shown in Figure 5. The burlap was soaked for 24 hours and wrung out to remove extra surface moisture prior to use. The use of burlap would keep the surface of the specimens wet while the concrete set and reduced the evaporation rate.

This method, however, presented a new problem. The burlap cover adhered to the surface of the specimen, altering the texture of the hardened concrete. The alteration was significant enough to limit the observation of settlement cracks, indicating that covering the surface with burlap would not be suitable for the study. A specimen that had been covered by burlap is shown in Figure 6.

Figure 5: Specimen Covered with Burlap

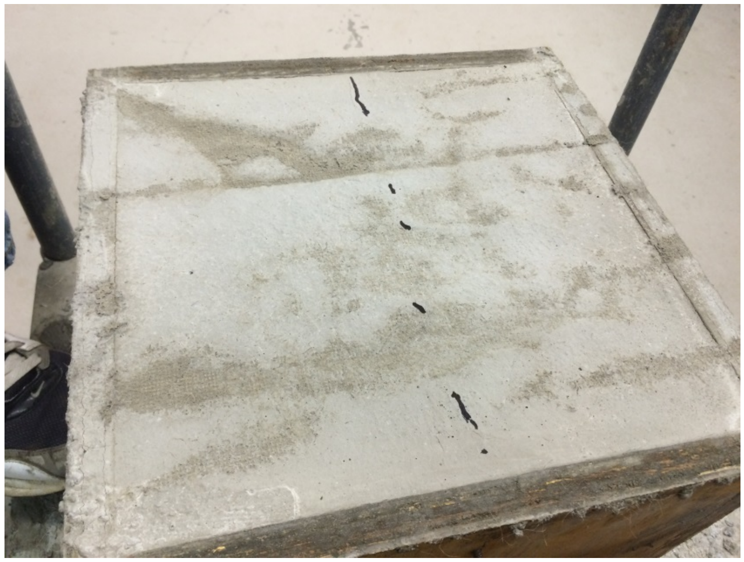

Figure 6: Surface of Specimen That Had Been Covered with Burlap (Black lines indicate crack locations)

<u>Specimens covered with hard plastic and enclosed in burlap and plastic sheeting</u>

For the next method evaluated, a piece of 14×14×0.25 in. hard plastic was added as a barrier between the surface of the concrete and the wet burlap. One in. thick foam inserts were placed at each corner to keep the plastic from touching the surface of the concrete. Placement of the hard plastic on the specimens is shown in Figure 7. The burlap was placed on top of the hard plastic, with a piece of plastic on top of the burlap and held in place by a rubber band as shown in Figure 8. This retained the benefits of the wet burlap cover while preventing the burlap from damaging the surface of the specimens.

Although there was no alteration of the surface due to the burlap, large surface defects did appear due to water droplets on the surface of completed specimens. This likely occurred due to water evaporating from the concrete, condensing the hard plastic, and dropping back onto the concrete surface. Once again, these surface defects prevented accurate readings. An example of the surface of a specimen as affected by the water droplets is shown in Figure 9.

Figure 7: Specimens Covered with Hard Plastic

Figure 8: Specimens Covered with Hard Plastic and Enclosed in Burlap and Plastic Sheeting

Figure 9: Surface as affected by Water Droplets

Specimens covered with sloped hard plastic and enclosed by burlap and plastic sheeting

To prevent surface damage due to water droplets, one side of the foam insulation was increased to a height of approximately 4 in. The hard plastic was then sloped at an angle of approximately 15 degrees. The placement of the sloped hard plastic on the specimens is shown in Figure 10. Adding a slope to the hard plastic allowed any condensed water to migrate to the lower edge of the plate and drop harmlessly onto the sides of the form. Specimens covered with sloped hard plastic and enclosed by burlap and plastic sheeting is shown in Figure 11.

Using this method, none of the specimens exhibited settlement cracking, even at very high slumps. This method could not be used for this study because there would be no way to determine the effect of slump, or measures used to limit settlement cracking.

Figure 10: Specimens Covered with Sloped Hard Plastic

Figure 11: Specimens Covered with Sloped Hard Plastic, Burlap, and Soft Plastic

Specimens covered with sloped hard plastic and enclosed in plastic sheeting

The final change during the development of the procedure was the elimination of the wet burlap. It is likely that the use of wet burlap maintained a relative humidity that was high enough for the concrete to swell, as it typically does at early ages when in a saturated condition. The swelling prevented cracks from appearing. The use of sloped hard plastic and plastic sheeting but without the burlap, however, still allowed for a high enough relative humidity in the region above the surface of the concrete so that plastic shrinkage cracking did not occur. Specimens covered with sloped hard plastic and plastic sheeting is shown in Figure 12.

This procedure did not cause surface defects, produced reasonable results, and was adopted for use in the study.

Figure 12: Specimen Covered with Sloped Hard Plastic and Enclosed in Plastic Sheeting

Readings

After of 24 hours, the specimens were removed from the environmentally controlled laboratory, and crack readings were taken. Only cracks that were directly above and parallel to the reinforcement were considered. The concrete was marked adjacent to the cracks using a permanent marker. The length of the cracks was measured with a ruler. The width of the widest crack was also measured using a crack comparator. The total crack length on a specimen was normalized with respect to the bar length (12 in.) and used as the principal basis of comparison between mixtures. An example of a specimen with the settlement cracks marked is shown in Figure 13.

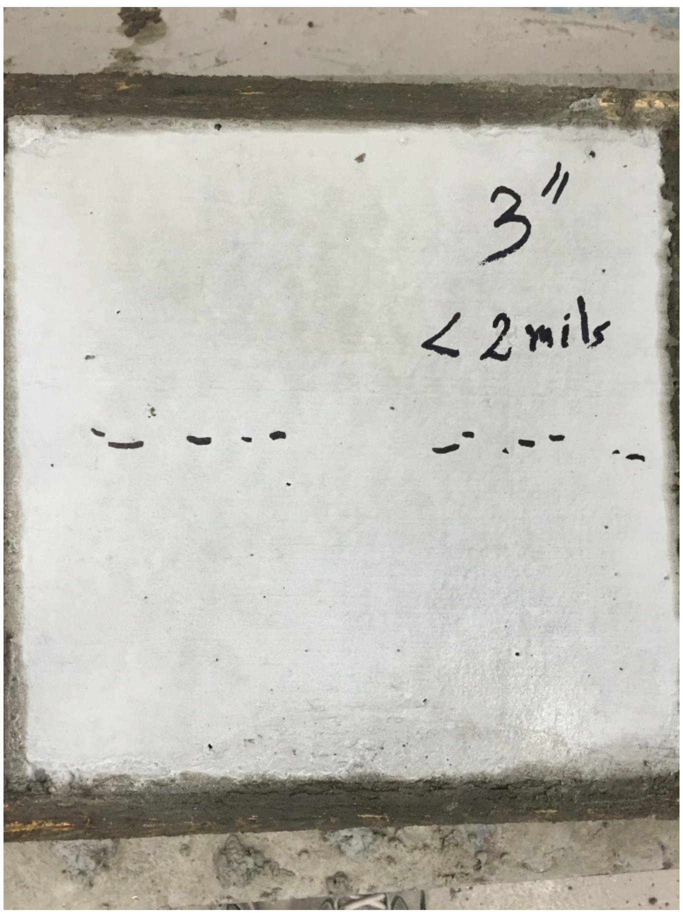

Figure 13: Settlement Cracking Specimen

RESULTS

This section presents the results of the settlement cracking tests for the specimens that were covered with sloped hard plastic and plastic sheeting. First, the results of the control mixtures are shown and discussed. Then the results of the mixtures containing Acti-Gel® 208 and FORTA-FERRO® fiber are presented and analyzed. All of the results are tabulated in Appendix B.

Control

The study began by testing multiple control mixtures to establish a suitable procedure and provide a standard for comparison. The results of the control mixtures are displayed in Figure 14. Crack lengths, normalized to bar length and averaged for three specimens, are plotted versus slump. A linear trend line and 20% error lines are also included in the plot for reference. One of the data points was considered an outlier because the corresponding specimens could not be finished properly due to low slump and incohesive concrete. Therefore, this outlier was not included when calculating the linear trend line.

Twenty-four control mixtures were tested with slumps ranging from 1¼ to 9 in. The crack lengths, normalized to bar length, varied from approximately 0.1 to 0.9. Three mixtures with slumps of 1¼ in. had an average crack length per bar length of approximately 0.2. At the other end of the spectrum, a mixture with a 9-in. slump had an average crack length per bar length of approximately 0.8. The results, however, exhibited significant scatter. The largest scatter in the data corresponds to the seven mixtures with slumps ranging from 4 to 5 in. that have normalized crack lengths of 0.73, 0.64, 0.64, 0.63, 0.42, 0.32, and 0.08. The six mixtures with slumps lower than 4 in. had normalized cracking ranging from 0.13 to 0.36. The ten mixtures with slumps higher than 5 in. had normalized cracking ranging from 0.42 to 0.88. Furthermore, half of the data points fall within the 20% error lines. Although there is scatter in the data, there is a clear correlation between increasing slump and increasing settlement cracking. The results agree with the conclusions of Dakhil et al. (1975).

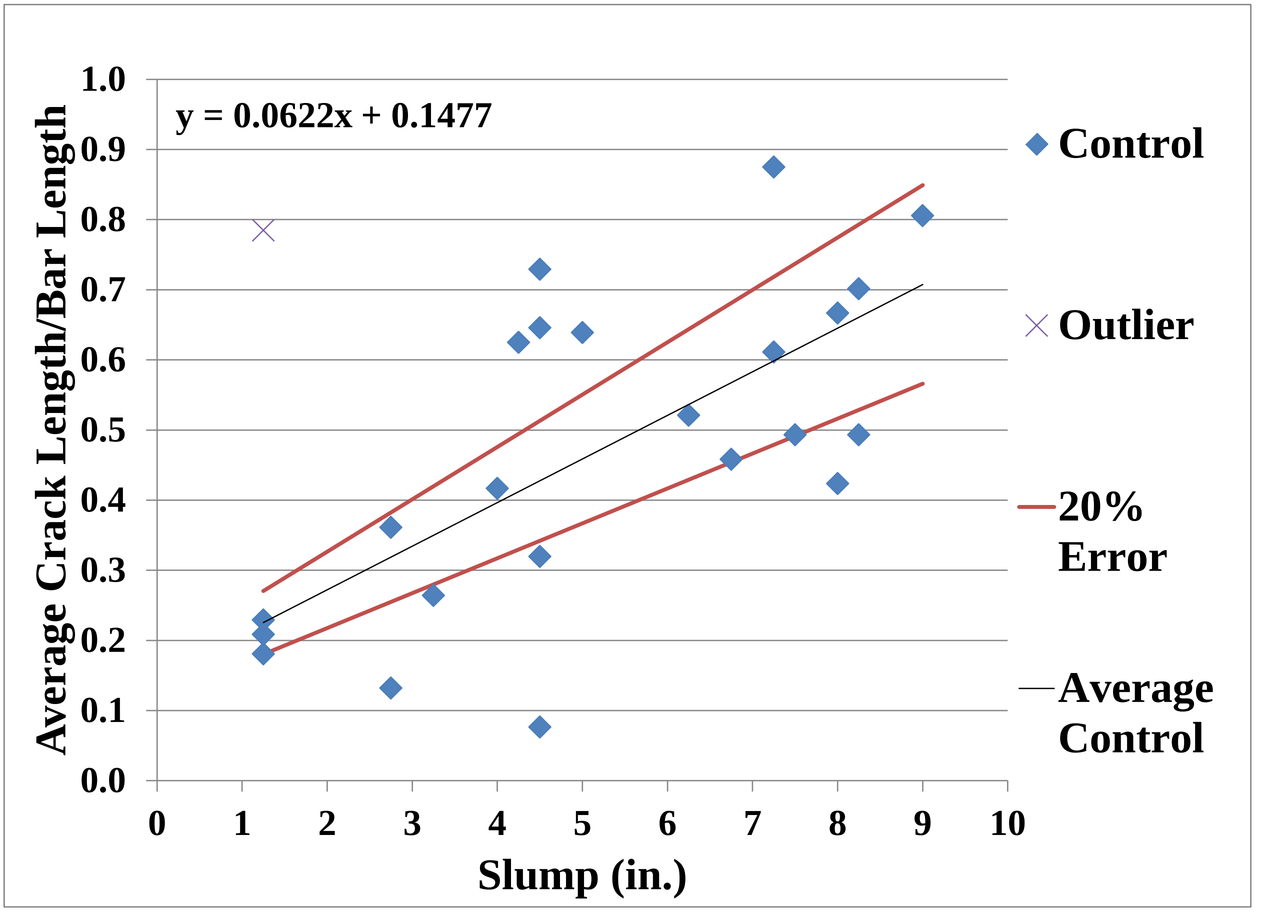

Figure 14: Average Normalized Cracking of Control Mixtures versus Slump

Acti-Gel® 208

The results of the mixtures containing Acti-Gel® 208 are displayed in Figure 15. The data for Acti-Gel® 208 are superimposed on that for the control mixtures. The linear trend line and 20% error lines for the control data are also included in the plot for reference.

Six Acti-Gel® 208 mixtures were tested with slumps ranging from $^{3}/_{4}$ to 8¼ in. The crack lengths, normalized to bar length, varied from approximately 0.04 to 0.4. Four of the mixtures had normalized crack lengths of approximately 0.1 or lower. The Acti-Gel® 208 mixture with a slump of ¾ in. had an average crack length per bar length below 0.05. On the other side of the spectrum, the mixture with an 8½ in. slump had an average crack length per bar length below 0.4. All of the mixtures containing Acti-Gel® 208 had average normalized crack lengths below the linear trend line for the control mixtures. Furthermore, only one of the mixtures containing Acti-Gel® 208 exhibited cracking that fell within the 20% error region of the control mixtures. There is scatter in the data, however, as the two mixtures with slumps of 3¾ and 4 in. had normalized cracking of 0.06 and 0.35, respectively.

Although the sample size is small, it appears that the addition of Acti-Gel® 208 tends to decrease the amount of settlement cracking in concrete. It is likely that the improved cohesion of the Acti-Gel® 208 mixtures contributed to the decrease in settlement cracking. However, further studies are planned to verify these results.

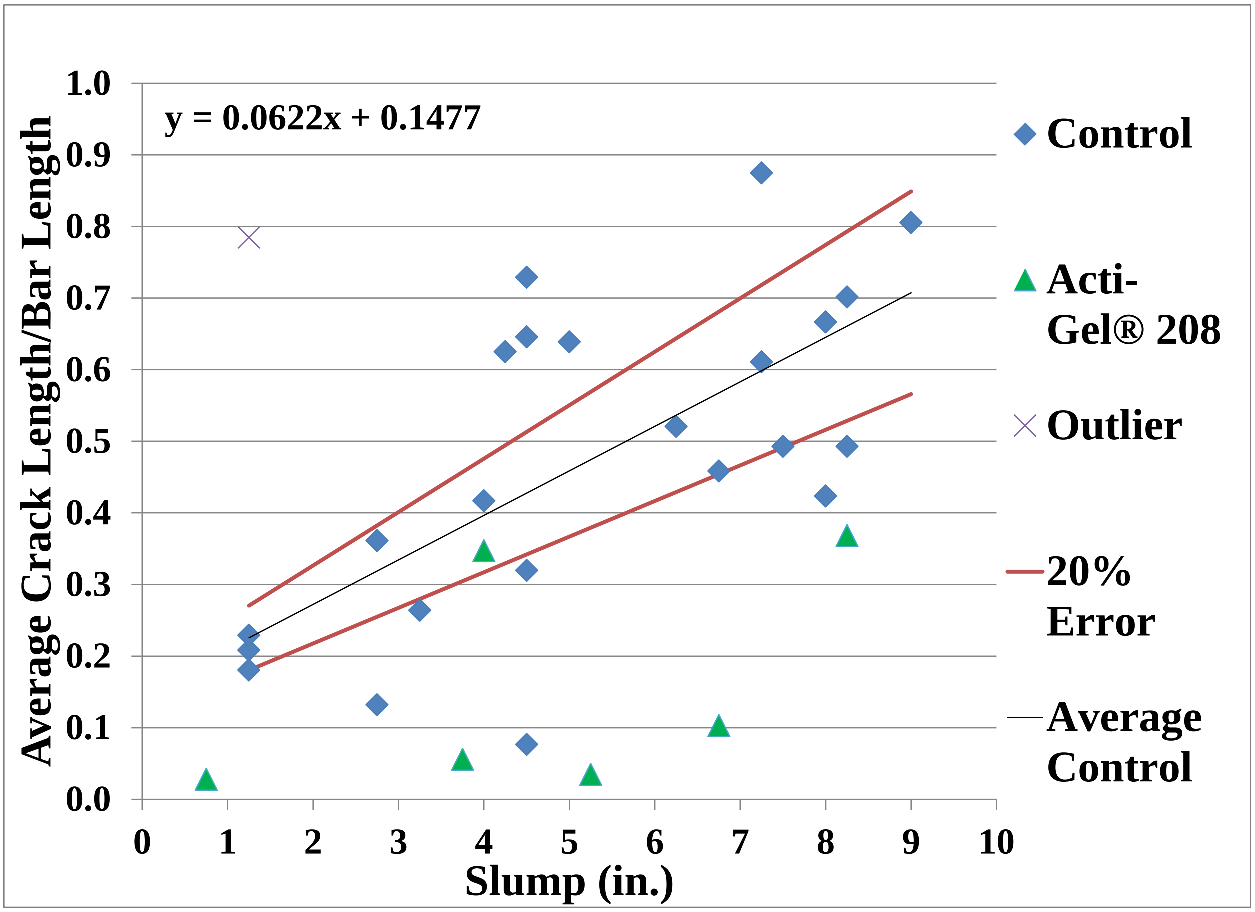

Figure 15: Average Normalized Cracking of Acti-Gel® 208 Mixtures versus Slump

FORTA-FERRO® Fibers

The results for the mixtures containing FORTA-FERRO® fibers are displayed in Figure 16. The data for the mixtures containing FORTA-FERRO® fibers are superimposed on the data for the control mixtures for comparison. The linear trend line and 20% error lines for the control data are also included in the plot for reference.

Eight FORTA-FERRO® fiber mixtures were tested with slumps ranging from ½ to 8 in. The crack lengths, normalized to bar length, varied from approximately 0.01 to 0.4. Four of the mixtures had normalized crack lengths of approximately 0.05 or lower. The FORTA-FERRO® fiber mixture with a slump of 1 in. had an average normalized crack length below 0.05. At the other end of the spectrum, a mixture with an 8-in. slump had an average crack length per bar length below 0.4. There is a significant amount of scatter in the data for the range of slumps from 6¾ to 8 in. as five mixtures have normalized cracking of 0.03, 0.05, 0.35, 0.38, and 0.38. All of the mixtures containing FORTA-FERRO® fibers had an average crack length per bar length that was lower than the linear trend line for the control mixtures, and only one of the mixtures containing FORTA-FERRO® fibers fell within the projection of the 20% error region of the control mixtures. This data point represents a mixture with a ½-in. slump, and may have been artificially high due to difficulty of finishing.

As with the mixtures containing Acti-Gel® 208, although the sample size is small, it appears that the addition of FORTA-FERRO® fiber to concrete also tends to decrease settlement cracking. The addition of FORTA-FERRO® fibers did not completely eliminate the incidence of cracking as reported for Fibermesh MD fibrillated propylene fibers by Suprenant and Malisch (1999). It is likely that the decrease in settlement cracking can be attributed to the fibers increasing the tensile strength of the plastic mixture and increasing the cohesiveness of the concrete. As for Acti-Gel® 208, further studies are planned.

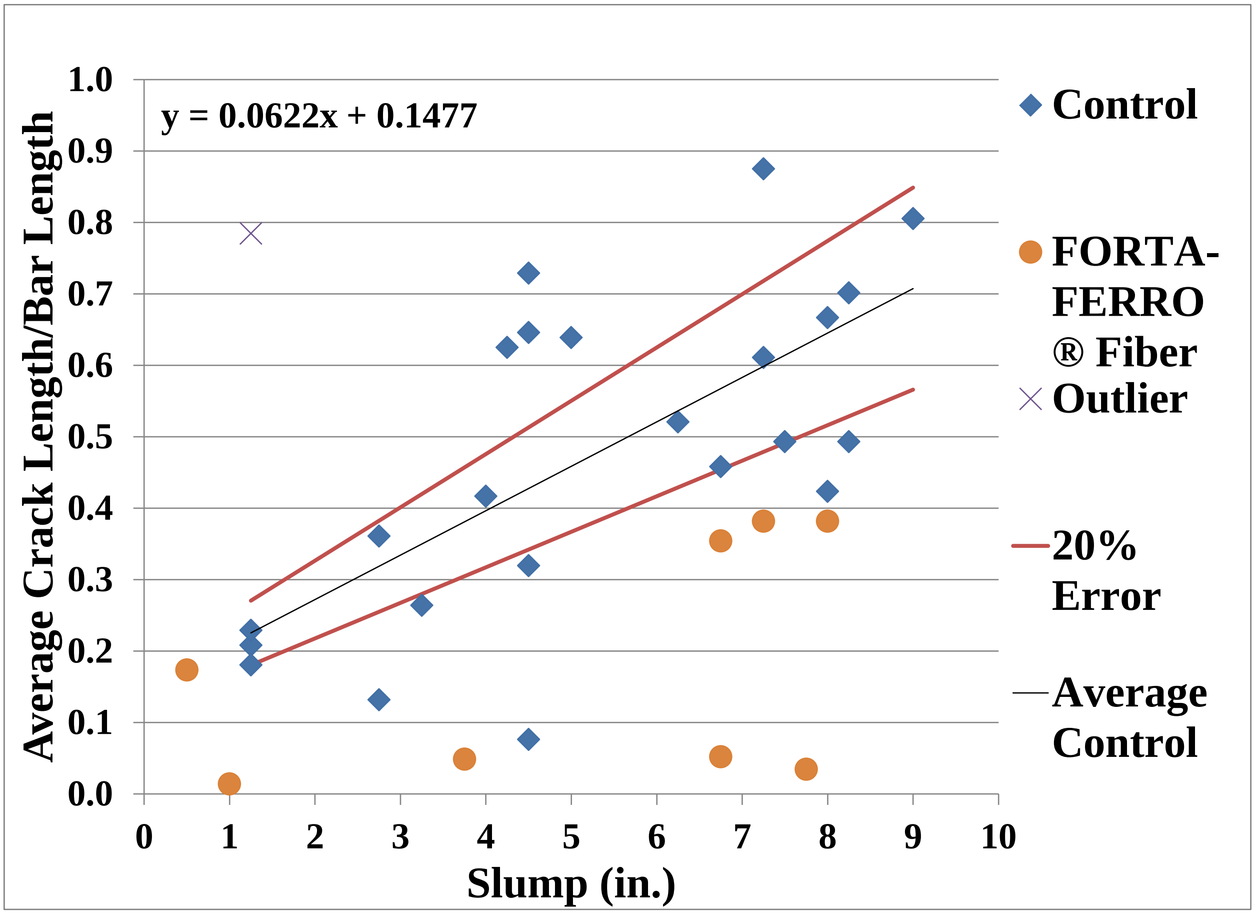

Figure 16: Average Normalized Cracking of FORTA-FERRO® Fiber Mixtures versus Slump

SUMMARY AND CONCLUSIONS

A laboratory procedure to test the settlement cracking performance of concrete was developed. The procedure was used to evaluate the effects of slump and the addition of either Acti-Gel® 208 or FORTA-FERRO® fibers on settlement cracking. The specimens consisted of 12×12×8 in. concrete blocks with No. 6 bars at 1.5 in. of cover to the center of the bar (nominal clear cover of $1^1/_8$ in.). Various methods of finishing and curing the specimens were investigated. The procedure was used to test 38 concrete mixtures with slumps ranging from ½ to 9 in. Of the 38 mixtures, 24 were control mixtures, 8 contained 2¼-in. FORTA-FERRO® fibers, and 6 contained Acti-Gel® 208. Average crack length, normalized to the bar length, was calculated for each mixture. The results were analyzed and compared to determine cracking trends.

The following conclusions are based on the experimental program and results from this study:

1. Covering specimens with sloped hard plastic enclosed by plastic sheeting provides for a concrete surface at 24 hours that allows for both formation and observation of settlement cracks, eliminating the effect of plastic shrinkage cracking, and allowing comparisons of different crack reducing technologies on settlement cracking.
2. Although there is scatter in the data, increasing slump increases the amount of settlement cracking.
3. Initial results show that the addition of Acti-Gel® 208 to concrete decreases the amount of settlement cracking.
4. Initial results show that the addition of FORTA-FERRO® fibers to concrete decreases the amount of settlement cracking.
5. There is a significant amount of scatter in the data for mixtures with similar slumps.

REFERENCES

Altowaiji, W. A. K., Darwin, D., and Donahey, R. C. (1986). "Bond of Reinforcement to Revibrated Concrete,"*Journal of the American Concrete Institute*, Vol. 83, No. 6, November-December, pp. 1035-1042.

American Society of Civil Engineering (ASCE) (2013). "Report Card for America's Infrastructure." *http://www.infrastructurereportcard.org/bridges/*

ASTM C70-13 (2013). "*Standard Test Method for Surface Moisture of Fine Aggregate*," ASTM International, West Conshocken, PA, 3 pp.

ASTM C127-12 (2012). "*Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*," ASTM International, West Conshocken, PA, 6 pp.

ASTM C143-12 (2012). "*Standard Test Method for Slump of Hydraulic-Cement Concrete*," ASTM International, West Conshocken, PA, 4 pp.

ASTM C192-12 (2012). "*Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*," ASTM International, West Conshocken, PA, 8 pp.

ASTM C1064-12 (2012). "*Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete*," ASTM International, West Conshocken, PA, 3 pp.

Babaei, K. and Fouladgar, A. M. (1997). "Solutions to Concrete Bridge Deck Cracking," *Concrete International*, Vol. 19, No. 7, July, pp. 34-37.

Bohaty, B., Riedel, E., and Darwin, D., 2013, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas," University of Kansas Center for Research, Lawrence, KS, December, 149 pp.

Combrink, R. and Boshoff, W. P. (2013). "The Origin of Plastic Settlement Cracking and the Effect of Re-vibration," *Research and Applications in Structural Engineering, Mechanics and Computation*, Taylor and Francis Group, London, England, pp. 617-618.

Dakhil, F. H., Cady, P. D., and Carrier, R. E. (1975). "Cracking of Fresh Concrete as Related to Reinforcement," *ACI Journal, Proceedings*, Vol. 72, No. 8, August, pp. 421-428.

Darwin, D., Browning, J., Lindquist, W., McLeod, H. A. K., Yuan, J., Toledo, M., Reynolds, D., 2010, "Low-Cracking, High-Performance Concrete Bridge Decks: Case Studies Over First 6 Years," *Transportation Research Record* 2202, December, pp. 61-69

Darwin, D., Browning, J., McLeod, H. A. K., Lindquist, W., Yuan, J., 2012, "Implementing Lessons Learned From Twenty Years of Bridge-Deck Crack Surveys," *Andy Scanlon Symposium* *on Serviceability and Safety of Concrete Structures: From Research to Practice*, SP-284, American Concrete Institute, Farmington Hills, MI, pp. 8-1-8-17

Gruman, D., Darwin, D., and Browning, J., 2009, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas," University of Kansas Center for Research, Lawrence, KS, January, 50 pp.

Harley, A., Darwin, D., and Browning, J., 2011, "Use of Innovative Concrete Mixes for Improved Constructability and Sustainability of Bridge Decks," University of Kansas Center for Research, Lawrence, KS, December, 79 pp.

Lindquist, W., Darwin, D., and Browning, J. (2005). "Cracking and Chloride Contents in Reinforced Concrete Bridge Decks," *SM Report* No. 78, University of Kansas Center for Research, Inc., Lawrence, Kansas, February, 453 pp.

Lindquist, W., Darwin D., and Browning J., 2008, "Development of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture Optimization, and Concrete Production" *SM Report* No. 92, University of Kansas Center for Research, KS, November, 504 pp.

McLeod, H. A. K., Darwin, D., and Browning, J., 2009, "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Construction Methods, Specifications, and Resistance to Chloride Ion Penetration" *SM Report* No. 94, University of Kansas Center for Research, Lawrence, KS, September, 848 pp.

Miller, G. G. and Darwin, D., 2000, "Performance and Constructability of Silica Fume Bridge Deck Overlays," *SM Report* No. 57, University of Kansas Center for Research, Lawrence, KS, January, 423 pp.

Pendergrass, B., Darwin, D., and Browning, J., 2014, "Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Shrinkage Reducing Admixtures, Internal Curing, and Cracking Performance," *SM Report* No. 107, University of Kansas Center for Research, Lawrence, KS, February, 625 pp.

Schmitt, T. R. and Darwin, D. (1995). "Cracking in Concrete Bridge Decks," *SM Report* No. 39, University of Kansas Center for Research, Inc., Lawrence, KS, April, 164 pp.

Schmitt, T. R. and Darwin, D. (1999). "Effect of Material Properties on Cracking in Bridge Decks," *Journal of Bridge Engineering*, ASCE, Vol. 4, No. 1, February, pp. 8-13

Suprenant, B. A. and Malisch, W. R. (1999). "The Fiber Factor – Lab Tests Show the Benefits of Using Synthetic Fibers to Limit Subsidence Cracking of Reinforced Concrete," *Concrete Construction*, October, 4 pp.

Transportation Research Board, (1979). "Durability of Concrete Bridge Decks," *National Cooperative Highway Research Program (NCHRP) Synthesis 57,* Transportation Research Board, National Research Council, Washington, D.C., 61 pp.

Weyers, R. E., Conway Jr., J. C., Cady, P. D. (1982). "Photoelastic Analysis of Rigid Inclusions in Fresh Concrete," *Cement and Concrete Research*, Vol. 12, No. 4, March, pp. 475-484

Yuan, J., Darwin D., and Browning, J., 2011, "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage Tests, Restrained Ring Tests, Construction Experience, and Crack Survey Results," *SM Report* No. 103, University of Kansas Center for Research, Lawrence, KS, September, 469 pp.

APPENDIX A

Mixture Proportions

Table A.1: Mixture Proportions

Batch S125

Date: 2/19/2015
Name: RB
Batch No. Batch S125
Batch volume: **0.095** yd^3

		Theoretical		Batch
Material Type	Material Name	Yd^3 batch (SSD) (lb)	Yd^3 batch ("wet") (lb)	Weight Used (lb)
C (cement)	Type I/II	500	500	47.50
W (water)	Water	250	210	19.92
Aggregate 1	Granite A	453	453	43.04
Aggregate 2	Granite B	893	893	84.84
Aggregate 3	Pea Gravel	576	586	55.71
Aggregate 4	Sand	1069	1099	104.40
Fibers	FORTA-FERRO®	3	3	0.29
AEA	MasterAir AE 200 (mL)	60	60	5.7
SuperPlastizier	MasterGlenium 3030 (mL)			100

APPENDIX B

SUMMARY OF SETTLEMENT CRACKING RESULTS

Table B.1: Settlement Cracking of Control Mixes

Mix #	Slump	Conc. Temp	Specimen Number	Settlement Cracks	Crack Width	Crack Length	Average Crack Length/Bar Length (in./in.)
S90	1.25	63	1	yes	<2 mils	0.25	
S90	1.25	63	2	yes	<2 mils	5.5	
S90	1.25	63	3	yes	<2 mils	1.75	0.208
S91	8	62	1	yes	<2 mils	6.25	
S91	8	62	2	yes	<2 mils	5	
S91	8	62	3	yes	<2 mils	4	0.424
S92	7.5	66	1	yes	<2 mils	3.75	
S92	7.5	66	2	yes	<2 mils	7.75	
S92	7.5	66	3	yes	<2 mils	6.25	0.493
S94	8.25	61	1	yes	<2 mils	8.5	
S94	8.25	61	2	yes	<2 mils	8.25	
S94	8.25	61	3	yes	<2 mils	8.5	0.701
S95	9	63	1	yes	<2 mils	9.25	
S95	9	63	2	yes	3 mils	9.5	
S95	9	63	3	yes	3 mils	10.25	0.806
S96	7.25	60	1	yes	<2 mils	7	
S96	7.25	60	2	yes	<2 mils	7.25	
S96	7.25	60	3	yes	<2 mils	7.75	0.611
S97	4.5	60	1	yes	<2 mils	9	
S97	4.5	60	2	yes	<2 mils	8	
S97	4.5	60	3	yes	<2 mils	9.25	0.729
S98	2.75	70	1	yes	2 mils	7.25	
S98	2.75	70	2	yes	<2 mils	2	
S98	2.75	70	3	yes	<2 mils	3.75	0.361
S99	8.25	68	1	yes	<2 mils	6.5	
S99	8.25	68	2	yes	<2 mils	3.5	
S99	8.25	68	3	yes	3 mils	7.75	0.493
S100	7.25	70	1	yes	5 mils	11.25	
S100	7.25	70	2	yes	5 mils	10.5	
S100	7.25	70	3	yes	5 mils	9.75	0.875
S101	1.25	68	1	yes	2 mils	10.25	
S101	1.25	68	2	yes	2 mils	9	
S101	1.25	68	3	yes	2 mils	9	0.785

Table B.1 (continued): Settlement Cracking of Control Mixes

Mix #	Slump	Conc. Temp	Specimen Number	Settlement Cracks	Crack Width	Crack Length	Average Crack Length/Bar Length (in./in.)
S109	1.25	70	1	yes	<2 mils	1	
S109	1.25	70	2	yes	<2 mils	5	
S109	1.25	70	3	yes	<2 mils	0.5	0.181
S110	4.25	66	1	yes	2 mils	6.75	
S110	4.25	66	2	yes	<2 mils	6.5	
S110	4.25	66	3	yes	<2 mils	9.25	0.625
S111	4.5	66	1	yes	<2 mils	3	
S111	4.5	66	2	yes	<2 mils	3	
S111	4.5	66	3	yes	2 mils	5.5	0.319
S112	1.25	67	1	yes	<2 mils	3.75	
S112	1.25	67	2	yes	<2 mils	1	
S112	1.25	67	3	yes	<2 mils	3.5	0.229
S113	6.75	65	1	yes	<2 mils	5.25	
S113	6.75	65	2	yes	<2 mils	5.75	
S113	6.75	65	3	yes	<2 mils	5.5	0.458
S114	5	69	1	yes	<2 mils	3.75	
S114	5	69	2	yes	<2 mils	8.5	
S114	5	69	3	yes	<2 mils	10.75	0.639
S115	4	65	1	yes	<2 mils	6.25	
S115	4	65	2	yes	<2 mils	4	
S115	4	65	3	yes	3 mils	4.75	0.417
S116	4.5	65	1	yes	<2 mils	0.5	
S116	4.5	65	2	no	0 mils	0	
S116	4.5	65	3	yes	2 mils	2.25	0.076
S117	2.75	65	1	yes	3 mils	2	
S117	2.75	65	2	yes	<2 mils	1.75	
S117	2.75	65	3	yes	<2 mils	1	0.132
S118	3.25	65	1	yes	<2 mils	3	
S118	3.25	65	2	yes	<2 mils	4	
S118	3.25	65	3	yes	<2 mils	2.5	0.264
S129	6.25	62	1	yes	2 mils	7.5	
S129	6.25	62	2	yes	2 mils	7	
S129	6.25	62	3	yes	<2 mils	4.25	0.521

Table B.1 (continued): Settlement Cracking of Control Mixes

Mix #	Slump	Conc. Temp	Specimen Number	Settlement Cracks	Crack Width	Crack Length	Average Crack Length/Bar Length (in./in.)
S133	4.5	68	1	yes	2 mils	7.75	
S133	4.5	68	2	yes	3 mils	11	
S133	4.5	68	3	yes	< 2 mils	4.5	0.646
S136	8	68	1	yes	2 mils	9.25	
S136	8	68	2	yes	2 mils	8.5	
S136	8	68	3	yes	2 mils	6.25	0.667

Table B.2: Settlement Cracking of Acti-Gel® 208 Mixes

Mix #	Initial Slump	Final Slump	Conc. Temp	Specimen Number	Settlement Cracks	Crack Width	Crack Length	Average Crack Length/Bar Length (in./in.)
S120	7.25	3.75	62	1	Yes	< 2 mils	1	
S120	7.25	3.75	62	2	Yes	< 2 mils	0.25	
S120	7.25	3.75	62	3	Yes	< 2 mils	0.75	0.056
S122	3.25	0.75	65	1	Yes	< 2 mils	0.75	
S122	3.25	0.75	65	2	Yes	< 2 mils	0.25	
S122	3.25	0.75	65	3	No	0	0	0.028
S124	8.25	5.25	63	1	Yes	< 2 mils	0.25	
S124	8.25	5.25	63	2	Yes	< 2 mils	0.25	
S124	8.25	5.25	63	3	Yes	2 mils	0.75	0.035
S128	9.5	8.25	66	1	Yes	3 mils	9.25	
S128	9.5	8.25	66	2	Yes	< 2 mils	0.75	
S128	9.5	8.25	66	3	Yes	2 mils	3.25	0.368
S131	8	6.75	68	1	Yes	< 2 mils	0.7	
S131	8	6.75	68	2	Yes	< 2 mils	1	
S131	8	6.75	68	3	Yes	< 2 mils	2	0.103
S134	6.75	4	67	1	Yes	2 mils	4.25	
S134	6.75	4	67	2	Yes	< 2 mils	4.5	
S134	6.75	4	67	3	Yes	< 2 mils	3.75	0.347

Table B.3: Settlement Cracking of FORTA-FERRO® Fiber Mixes

Mix #	Initial Slump	Final Slump	Conc. Temp	Specimen Number	Settlement Cracks	Crack Width	Crack Length	Average Crack Length/Bar Length (in./in.)
S119*	8	6.75	63	1	Yes	< 2 mils	0.5	
S119	8	6.75	63	2	Yes	< 2 mils	0.75	0.052
S121	8.25	6.75	64	1	Yes	< 2 mils	4.25	
S121	8.25	6.75	64	2	Yes	< 2 mils	1.75	
S121	8.25	6.75	64	3	Yes	< 2 mils	6.75	0.354
S123	7.5	3.75	65	1	Yes	< 2 mils	0.25	
S123	7.5	3.75	65	2	Yes	< 2 mils	0.25	
S123	7.5	3.75	65	3	Yes	< 2 mils	1.25	0.049
S125	9	7.75	64	1	Yes	< 2 mils	0.25	
S125	9	7.75	64	2	Yes	< 2 mils	0.25	
S125	9	7.75	64	3	Yes	< 2 mils	0.75	0.035
S127	1.5	0.5	67	1	Yes	2 mils	4.5	
S127	1.5	0.5	67	2	Yes	< 2 mils	1.5	
S127	1.5	0.5	67	3	Yes	< 2 mils	0.25	0.174
S130	3	1	67	1	Yes	< 2 mils	0.25	
S130	3	1	67	2	No	0	0	
S130	3	1	67	3	Yes	< 2 mils	0.25	0.014
S132	9.5	8	66	1	Yes	2 mils	7.25	
S132	9.5	8	66	2	Yes	2 mils	5.5	
S132	9.5	8	66	3	Yes	< 2 mils	1	0.382
S135	8.25	7.25	68	1	Yes	2 mils	5.5	
S135	8.25	7.25	68	2	Yes	2 mils	8.25	
S135	8.25	7.25	68	3	No	0	0	0.382

*S119 had only two specimens